

# Search for Neutrinoless Double Beta Decay with NEMO 3 and SuperNEMO

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**Abstract.** Since 2003 the NEMO 3 experiment has been searching for neutrinoless double beta decay using about 10 kg of enriched isotopes. A limit of  $T_{1/2}^{0\nu} > 5.8 \times 10^{23}$  years at 90% CL has been obtained for  $^{100}\text{Mo}$  from the first two years of data. Several measurements of  $2\nu\beta\beta$  decays have also been performed. A first NEMO 3 measurement of the  $2\nu\beta\beta$  half-life of  $^{130}\text{Te}$  is presented, giving a value of  $T_{1/2}^{2\nu} = (7.6 \pm 1.5(\text{stat}) \pm 0.8(\text{syst})) \times 10^{20}$  years. In parallel, there is an active R&D programme for the SuperNEMO experiment which is expected to commence data taking in 2012–2013 with 100–200 kg of enriched isotopes.

## 1. Introduction

Neutrinoless double beta decay ( $0\nu\beta\beta$ ) leads to the decay of a nucleus of charge  $Z$  and atomic number  $A$  via the process  $(A, Z) \rightarrow (A, Z+2) + 2e^-$ . This decay violates total lepton number  $L$ . Its observation would therefore be a direct indication for physics beyond the Standard Model. Neutrinos would be Majorana and not Dirac particles, thereby solving one of the fundamental questions of particle physics. The  $0\nu\beta\beta$  half-life is given by

$$\frac{1}{T_{1/2}^{0\nu}(A, Z)} = |M^{0\nu}(A, Z)|^2 G^{0\nu}(Q, Z) \langle m_{\beta\beta} \rangle^2, \quad (1)$$

where  $M^{0\nu}(A, Z)$  is the nuclear matrix element (NME) and  $G^{0\nu}(Q, Z)$  is a known phase space factor that depends on the  $Q$ -value of the process. The half-life is proportional to the squared effective Majorana mass,  $\langle m_{\beta\beta} \rangle^2$ , which is given by a sum over the masses  $m_i$  of the mass eigenstates,  $\langle m_{\beta\beta} \rangle = \sum_{i=1,2,3} U_{ei}^2 m_i$ , weighted by the squared elements,  $U_{ei}^2$ , of the PMNS neutrino mixing matrix. The pairing term in the nuclear binding energy leads to a splitting of the parabola describing the binding energy for isobaric nuclei with even  $A$ . Beta decay is therefore forbidden or strongly suppressed for even-even nuclei, making them the only candidates for observing  $0\nu\beta\beta$  decays.

## 2. NEMO-3

The NEMO 3<sup>1</sup> experiment has been taking data since 2003 in the Modane Underground Laboratory (LSM) located in the Frejus tunnel at a depth of 4800 m water equivalent. The experiment has a cylindrical shape with 20 sectors that contain different isotopes in the form of thin foils with a total surface of about 20 m<sup>2</sup> (Table 1). The main isotopes used for the  $0\nu\beta\beta$

<sup>1</sup> Neutrino Ettore Majorana Observatory

search are about 7 kg of  $^{100}\text{Mo}$  and about 1 kg of  $^{82}\text{Se}$ . Smaller amounts of other isotopes are mainly used for measuring the  $2\nu\beta\beta$  process. Tellurium and copper foils are used for background measurements. On each side of the foils is a  $\sim 50$  cm wide tracking volume consisting of a total

**Table 1.** Isotopes used in NEMO 3.

	$^{100}\text{Mo}$	$^{82}\text{Se}$	$^{116}\text{Cd}$	$^{96}\text{Zr}$	$^{150}\text{Nd}$	$^{48}\text{Ca}$	$^{130}\text{Te}$	$^{\text{nat}}\text{Te}$	Cu
mass [g]	6914	932	405	9.4	37.0	7.0	454	491	621
$Q$ [keV]	3034	2995	2805	3350	3367	4772	2529		

of 6180 drift cells operated in Geiger mode with a typical vertex resolution of 5 mm and 8 mm in the coordinates transverse and perpendicular to the foil, respectively. The drift gas is helium with admixtures of 4% ethyl alcohol, 1% argon and 0.1% water. A 25 Gauss magnetic field created by a solenoid provides charge identification. The calorimeters comprises 1940 plastic scintillators coupled to low radioactivity photomultipliers. For 1 MeV electrons the energy resolution (FWHM) ranges from 14.1% to 17.7% and the timing resolution is 250 ps. The timing measurement is used to identify background sources originating from outside the foils (external background). Identification of photons, electrons, positrons and alpha particles is a powerful tool to reject internal background from the foil and other background from inside the detector volume. In the data analysis the kinematics of the different background sources are simulated using Monte Carlo generators. The rates are determined from HPGe measurements of the material and through measurements of control channels such as the emission of an electron in association with a photon or an alpha particle.

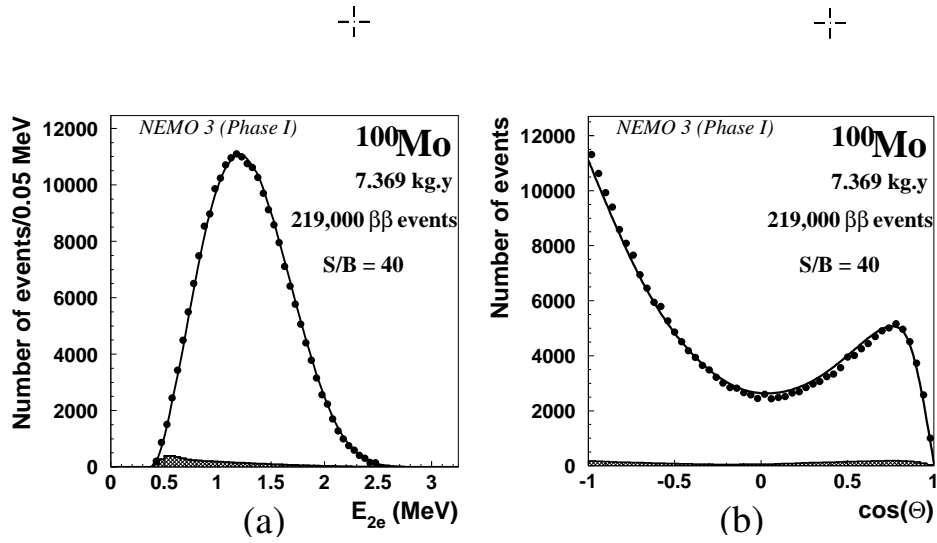
A major background is due to the  $\beta$  decay of  $^{214}\text{Bi}$  which has a high  $Q$ -value of 3.27 keV. It is produced in the decay chain of radon outgassed by the rock surrounding the detector. Radon purification has been obtained using charcoal filters trapping radon which subsequently decays in the filter with a half-life of 3.8 days. The  $^{214}\text{Bi}$  contamination can be measured using the BiPo process, where  $^{214}\text{Bi}$  decays into  $^{214}\text{Po}$  via  $\beta$  decay and subsequently, with a half-life of 164  $\mu\text{s}$ , into  $^{210}\text{Pb}$ . Measurements of this process demonstrate that the radon contamination has been significantly decreased since the installation of the radon filter in October 2004 (phase II). The data taken before October 2004 are labeled phase I.

### 2.1. Measurement of $2\nu\beta\beta$ decays

The NEMO 3 experiment is in the unique position to perform high statistics measurements of  $2\nu\beta\beta$  decays,  $(A, Z) \rightarrow (A, Z+2)+2e^-+2\nu$  [2].<sup>2</sup> These measurements improve the understanding of the  $2\nu\beta\beta$  process which is the ultimate background in the  $0\nu\beta\beta$  search. Its contribution can only be reduced by improving the energy resolution. Furthermore, the measured  $2\nu\beta\beta$  rates help to constrain nuclear models and NME calculations which are currently a source of large uncertainty when translating the  $0\nu\beta\beta$  half-lives into an effective Majorana neutrino mass,  $\langle m_{\beta\beta} \rangle$  (Eq. 1). The distribution of the energy sum of the two electrons and their angular distribution are shown in Fig. 1 for  $^{100}\text{Mo}$  [3]. The agreement of the data with a  $2\nu\beta\beta$  simulation is generally good apart from a small shift in the angular distribution. The measured  $^{100}\text{Mo}$  half-life is  $T_{1/2}^{2\nu} = (7.11 \pm 0.02(\text{stat}) \pm 0.54(\text{syst})) \times 10^{18}$  years.

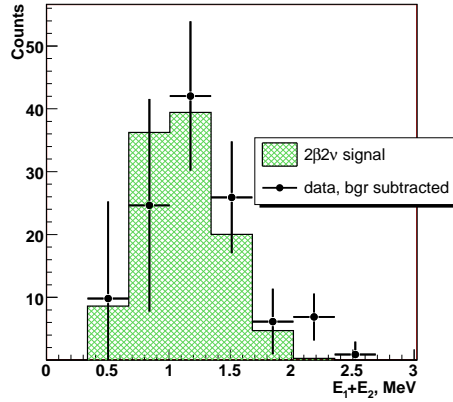
The  $2\nu\beta\beta$  half-life of  $^{130}\text{Te}$  has been a long-standing mystery due to the wide range of measurements using geochemical sources. The half-life seems to depend on the age of the

<sup>2</sup> This process is not the same as two subsequent  $\beta$  decays, which would be energetically forbidden. It was first predicted in 1935 by Goeppert-Mayer [1].



**Figure 1.** Distributions of the a) energy sum,  $E_{12}$ , and b) angular variable,  $\cos \theta$ , of the two electrons observed in  $^{100}\text{Mo}$  decays. The phase I data are shown as points, the subtracted background as hashed histogram. The data are compared to  $2\nu\beta\beta$  Monte Carlo.

sample used,  $\simeq 7 - 9 \times 10^{20}$  years [4] for samples with an age of the order 100 million years and  $\simeq 25 - 27 \times 10^{20}$  years [5] for samples older than 1 billion years. It has even been speculated that this could be related to time dependence of the Fermi constant,  $G_F$ . A discussion of the measurements can be found in [6]. The first indication of a positive result in  $^{130}\text{Te}$  was obtained using  $\text{TeO}_2$  crystals and yielded a value  $T_{1/2}^{2\nu} = (6.1 \pm 1.4(\text{stat}) \pm_{3.5}^{2.9}(\text{syst})) \times 10^{18}$  years [7].



**Figure 2.** Distribution of the energy sum,  $E_{12}$ , of the two electrons observed in  $^{130}\text{Te}$  decays after background subtraction (phase I + phase II, 534 days).

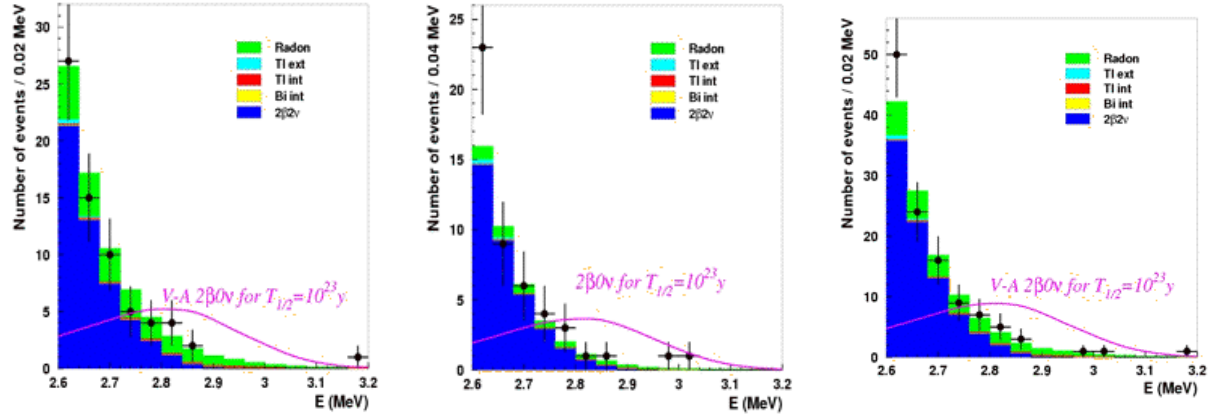
A more accurate measurement of the  $2\nu\beta\beta$  half-life has recently been performed by NEMO 3 using 454 g of  $^{130}\text{Te}$ . The data, corresponding to 534 days, are shown in Fig. 2 after background subtraction. The background subtracted distribution contains  $109 \pm 22$  events. This corresponds to  $T_{1/2}^{2\nu} = (7.6 \pm 1.5(\text{stat}) \pm 0.8(\text{syst})) \times 10^{20}$  years. The value is consistent with the measurement of [7] and with the lower values of the geochemical experiments. An overview of all  $2\nu\beta\beta$  half-lives measured by NEMO 3 is given in Table 2.

**Table 2.** Half-life of  $2\nu\beta\beta$  measured using the phase I data taken by NEMO 3 (360 days). The  $^{130}\text{Te}$  measurement uses phase I and phase II data (534 days)

isotope	signal/background	$T_{1/2}$ [ $10^{19}$ years]
$^{100}\text{Mo}$	40	$0.711 \pm 0.002$ (stat) $\pm 0.054$ (syst)
$^{82}\text{Se}$	4	$9.6 \pm 0.3$ (stat) $\pm 1.0$ (syst)
$^{116}\text{Cd}$	7.5	$2.8 \pm 0.1$ (stat) $\pm 0.3$ (syst)
$^{150}\text{Nd}$	2.8	$0.97 \pm 0.07$ (stat) $\pm 0.1$ (syst)
$^{96}\text{Zr}$	1	$2.0 \pm 0.3$ (stat) $\pm 0.2$ (syst)
$^{48}\text{Ca}$	$\sim 10$	$3.9 \pm 0.7$ (stat) $\pm 0.6$ (syst)
$^{130}\text{Te}$	0.25	$76 \pm 15$ (stat) $\pm 8$ (syst)

## 2.2. Search for Neutrinoless Double Beta Decay

The distribution of the energy sums,  $E_{12}$ , of the two electrons is used to search for neutrinoless double beta decay. A signal would correspond to an excess at  $E_{12} \approx Q$ , smeared out by the energy resolution of the calorimeter. A Monte Carlo simulation of a signal is shown in Fig. 3 for  $^{100}\text{Mo}$ . The number of background events expected in the energy window  $2.8 < E_{12} < 3.2$  MeV is 12.1 for the sum of phase I and II, corresponding to 693 days of data taking, and the number of observed events is 11. Limits on the half-life are set using a maximum likelihood technique, yielding  $T_{1/2}^{0\nu} > 5.8 \times 10^{23}$  years at 90% Confidence Level (CL). Depending on the values of NME used [10], this translates into a limit on the neutrino mass of  $\langle m_{\beta\beta} \rangle < 0.8 - 1.3$  eV. In 2006, the collaboration has decided to perform a blind analysis with the current data set and plans to update the results in summer 2008 and again in early 2010.



**Figure 3.** Distribution of the energy sum,  $E_{12}$ , of the two electrons for  $^{100}\text{Mo}$ . The data are shown as points,  $2\nu\beta\beta$  background is shown in blue, the radon induced background in green and the signal distribution in magenta. a) phase I (394 days, high radon); b) phase II (299 days, low radon); c) phase I+II (693 days).

Another possibility for neutrinoless double beta decays is Majoron emission,  $(A, Z) \rightarrow (A, Z+2) + 2e^- + \chi^0$  [8]. Majorons are Goldstone bosons arising due to the spontaneous breaking of the global  $B-L$  symmetry, where  $B$  is the baryon number. Other possibilities for  $0\nu\beta\beta$  decay arise in supersymmetric models with  $R$ -parity violation with the emission of two  $\chi^0$  [9]. Limits

are expressed in terms of the spectral index  $n$ , which is defined by the phase space of the emitted particles,  $G^{0\nu} \sim (Q - E_{12})^n$ . The distribution of the energy sum is distorted depending on the spectral index  $n$  and the limits are set using a maximum likelihood method. The limits are given in Table 3. For single Majoron emission, the half-life  $T_{1/2}^{-1}$  is proportional to  $|\langle g_{ee} \rangle|^2$ , where  $g_{ee}$  is the Majoron-neutrino coupling constant. For the case  $n = 1$  limits of  $\langle g_{ee} \rangle < (0.4 - 1.9) \times 10^{-4}$  and  $\langle g_{ee} \rangle < (0.66 - 1.7) \times 10^{-4}$  are obtained for  $^{100}\text{Mo}$  and  $^{82}\text{Se}$ , respectively. Limits have also been set on an admixture of a right-handed current in the Lagrangian.

**Table 3.** Limits on the half-life at 90% CL for models with Majoron emission, where  $n$  is the spectral index (phase I data) and on a right-handed (V+A) contribution in the Lagrangian.

isotope	$n = 1$	$n = 2$	$n = 3$	$n = 7$	V + A
$^{100}\text{Mo}$	$2.7 \times 10^{22} \text{ y}$	$1.7 \times 10^{22} \text{ y}$	$1.0 \times 10^{22} \text{ y}$	$7 \times 10^{19} \text{ y}$	$3.2 \times 10^{23} \text{ y}$
$^{82}\text{Se}$	$1.5 \times 10^{22} \text{ y}$	$6.0 \times 10^{21} \text{ y}$	$3.1 \times 10^{21} \text{ y}$	$5.0 \times 10^{20} \text{ y}$	$1.2 \times 10^{23} \text{ y}$

### 3. SuperNEMO

The SuperNEMO experiment will be based on the successful NEMO 3 concept. The unique features of this tracking plus calorimetry approach are:

- Measurement of process kinematics:  
The measurement of the main kinematic observables, the individual electron energies and their angular correlation will be used to study the underlying physics mechanism (e.g. SUSY, right-handed currents) of the  $0\nu\beta\beta$  process.
- Sources separated from the detector:  
This allows to measure several isotopes. This is essential to reduce systematic uncertainties, to confirm a  $0\nu\beta\beta$  discovery and to identify the underlying physics mechanism.
- Particle identification:  
Electron, positron, gamma and alpha identification are powerful tools for background rejection. Photon identification is used to reject any unknown nuclear gamma line.

The SuperNEMO Collaboration comprises about 60 physicists from 12 countries. Major R&D projects have been approved in France and the UK. The preliminary SuperNEMO design is based on a planar, modular geometry with 20 modules each containing about 5 kg of enriched isotopes. The main challenges for the SuperNEMO design are addressed in this R&D project:

- Improvement of the the calorimeter energy resolution to 4% at electron energies of 3 MeV is necessary to discriminate  $0\nu\beta\beta$  decays from background. To accomplish this goal, several ongoing studies are investigating the choice of calorimeter parameters such as scintillator material, the shape, size and coating of calorimeter blocks, combined with low radioactivity photomultipliers with high quantum efficiency. Initial studies have demonstrated excellent energy resolution ( $\sim 6.5\%$  at 1 MeV) for small size samples; the focus is now to retain this property in larger blocks.
- The tracker will consist of Geiger cells similar to NEMO 3 with a length of  $\sim 4$  m. Several smaller prototypes have been built and successfully operated to optimize the design of the tracker, including the cell size, wire geometry and wire diameters. Large prototypes ( $\sim 100$ – $300$  cells) will be constructed in the near future. In parallel, a wiring robot is being designed and tested to allow for large scale production.

**Table 4.** A comparison of the main NEMO 3 and SuperNEMO parameters.

	NEMO 3	SuperNEMO
isotope	$^{100}\text{Mo}$	$^{150}\text{Nd}$ or $^{82}\text{Se}$
mass	7 kg	100–200 kg
signal efficiency	8%	> 30%
$^{208}\text{Tl}$ in foil	< $20\mu\text{Bq/kg}$	< $2\mu\text{Bq/kg}$
$^{214}\text{Bi}$ in foil	< $300\mu\text{Bq/kg}$	< $10\mu\text{Bq/kg}$ ( $^{82}\text{Se}$ )
energy resolution (FWHM at 3 MeV)	8%	4%
half-life	$T_{1/2}^{0\nu} > 2 \times 10^{24}$ years	$T_{1/2}^{0\nu} > 2 \times 10^{26}$ years
neutrino mass	$\langle m_{\beta\beta} \rangle < 0.3 - 1.3$ eV	$\langle m_{\beta\beta} \rangle < 50 - 110$ meV

- The choice of isotope is based on a set of parameters: a long  $2\nu\beta\beta$  half-life, a high  $Q$ -value, a large phase space factor  $G^{0\nu}$  and a large NME. The enrichment possibility on a large scale is also a factor in selecting the isotope. The main candidate isotopes have emerged to be  $^{82}\text{Se}$  and  $^{150}\text{Nd}$ . As sample of 4 kg of  $^{82}\text{Se}$  has been enriched and is currently undergoing purification. The collaboration is investigating the possibility of enriching large amounts of  $^{150}\text{Nd}$  via the method of atomic laser isotope separation.
- Ultra-low background levels are of paramount importance for the discovery potential of SuperNEMO. The source foils must be pure and their radioactive contamination must be precisely measured. The most important contaminants are  $^{208}\text{Tl}$  and  $^{214}\text{Bi}$ . To measure their activities, dedicated detectors for the BiPo process (see Section 2) are developed. The first BiPo prototype was installed in the Canfranc laboratory in 2006.

The improvements expected when going from NEMO 3 to SuperNEMO are given in Table 4. Based on the results from the ongoing R&D projects, including detailed detector and physics simulations, a Technical Design Report (TDR) will be written in 2009. First modules can be installed as early as 2010 and all twenty modules will be running by 2012–2013.

#### 4. Summary

The NEMO approach of using tracking plus calorimetry is unique for a  $0\nu\beta\beta$  experiment and allows for excellent background rejection, choice of multiple isotopes and full kinematic reconstruction. NEMO 3 is taking data, measuring the  $2\nu\beta\beta$  process for several nuclei and setting limits on the half-life of the  $0\nu\beta\beta$  process. At the same time there is an active R&D programme for the next-generation experiment SuperNEMO.

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